NAL PROPOSAL No. 0030

Correspondent: T. Kirk
Department of Physics
Harvard University
Cambridge, Mass. 02138

FTS/Off-net: 617-223-2100
868-1020

Neutral Kaon Regeneration
In Liquid Hydrogen from 40 GeV to 200 GeV

T. B. W. Kirk, J. E. Pilcher, L. Verhey, R. Wilson
Harvard University

T. L. Collins
National Accelerator Laboratory

June, 1970

Neutral Kaon Regeneration In Liquid Hydrogen from 40 GeV to 200 GeV

Experimental Proposal to National Accelerator Laboratory

by

Thomas B. W. Kirk, James E. Pilcher, Lynn Verhey, Richard Wilson of Harvard University

and

Thomas L. Collins, National Accelerator Laboratory

Address for Correspondence:

Dr. Thomas Kirk
Department of Physics
Harvard University
Cambridge, Mass. 02138

CONTENTS

PERSONNEL

From Harvard University

Richard Wilson	Professor
T. Kirk	Assistant Professor
J. Pilcher	Assistant Professor
L. Verhey	Research Fellow

one or more graduate students and probably one more research fellow

Professor C. Rubbia has agreed to help with the experiment and apparatus, during September 1970-July 1971. He is unable to commit himself to work on the experiment itself because of prior commitments to the ISR at CERN. He will join in the experiment only if scheduling permits.

From NAL

Thomas L. Collins	Associate Director

It is our intention to collaborate in this experiment with Professor A. Wattenberg and his group at the University of Illinois. Practical difficulties have made a joint document not feasible in this first instance, but we have agreed to proceed together, and expect to combine the two proposals into a single document at a later stage.

ABSTRACT

We propose to investigate the asymptotic properties of the $K_o p$ and $\overline{K}_o p$ cross sections from 40 GeV to 200 GeV by the method of neutral kaon regeneration in liquid hydrogen. Both the difference in total cross section and the regeneration phase will be determined to a precision of better than 10% up to approximately 160 GeV, and with decreasing precision to 200 GeV.

The apparatus we propose to use is of a standard reliable type. The neutral beam is derived from a target intercepting 10^{11} protons at 400 GeV in the main accelerator ring. In this way, an experiment of major importance can be done very early in the NAL program which cannot otherwise be attempted until the advent of Area III.

I. Neutral Kaon Regeneration at 400 GeV

In this experiment we propose to measure $K_L \rightarrow K_S$ regeneration on hydrogen at energies from 40 GeV to 200 GeV; both the magnitude and the phase will be determined. The magnitude comes directly, and the phase comes from interference with the CP violating amplitude $K_L \rightarrow \pi^+\pi^-$.

Much intensive study has been and is being made of the CP violating amplitudes. They are well enough known now, and will become better known. We assume below that they are known.

The amplitude for regenerating K_S from K_L, in a finite regenerator, depends upon the <u>difference</u> of the K_oP and $\overline{K_o}P$ forward scattering amplitudes:

$$\rho = \frac{i\pi N\Lambda_S[f(0°)-\tilde{f}(0°)]}{k}\left[\frac{1-e^{(i\Delta m\tau_s-\frac{1}{2})L/\Lambda_s}}{\frac{1}{2}-i\Delta m\tau_s}\right] \qquad 1\text{-}1$$

where in this formula:

k = deBroglie wave number (cm)

P/k = momentum of laboratory kaon

τ_s = lifetime of K_S in its own Lorentz frame

are variables and:

N = macroscopic nuclear density (protons/cm^3)

Λ_s = laboratory K_S decay length (cm)

f = nuclear scattering amplitude (cm)

$\Delta m = m_L - m_S$ (units of τ_S)

L = length of regenerator in laboratory (cm)

are constants, either measured or assumed well known. The optical theorem can be applied to this formula to yield:

$$\rho = \frac{N\Lambda_S\ \Delta\sigma}{4\ \sin\phi_f}\left[\frac{1 - e^{(i\Delta m\tau_S - \frac{1}{2})L/\Lambda_S}}{\frac{1}{2} - i\Delta m\tau_S}\right] e^{i(\phi_f - \frac{\pi}{2})} \qquad 1\text{-}2$$

where:

$$\Delta\sigma \equiv \sigma_{total}(K_o p) - \sigma_{total}(\overline{K_o} p) \qquad 1\text{-}3$$

$$\sin\phi_f \equiv \quad \mathrm{Im}\ i[f(0°)-\bar{f}(0°)] / |f(0°)-\bar{f}(0°)| \qquad 1\text{-}4$$

This is the regeneration amplitude just at the downstream edge of the regenerator normalized to the outgoing K_L flux. At a distance z downstream of this edge, the regenerated K_S amplitude interferes with the CP violating $K_L \to \pi^+\pi^-$ amplitude to oroduce an intensity pattern given by:

$$I_{+-}(z,Pk) = |\rho|^2 e^{-z/\Lambda_S} + |\eta_{+-}|^2 e^{-z/\Lambda_L} + 2|\rho|\ |\eta_{+-}|\ e^{-z/2\Lambda_S} \times$$

$$\times \quad \cos\ [\Delta m\tau - \phi_{+-} + \phi_o] \qquad 1\text{-}5$$

where:

Λ_S, Λ_L = laboratory decay length of K_S, K_L (cm)

η_{+-} = CP violation parameter

ϕ_{+-} = phase of η_{+-}

τ = proper time from regenerator edge

$\phi_\rho = \phi_f + \phi_L$

The basic phase we are interested in is ϕ_f which is defined by:

$$\phi_f \equiv \text{Arg}\ \{i[f(0°)-\overline{f}(0°)]\} \qquad 1\text{-}6$$

The phase ϕ_L is an artifact of the finite regenerator length given by:

$$\phi_L = \text{Arg}\left[\frac{1 - e^{(i\Delta m\tau_S - \frac{1}{2})L/\Lambda_S}}{\frac{1}{2} - i\Delta m\tau_S}\right] \qquad 1\text{-}7$$

Our technique is conventional. We will measure each pion in the $\pi^+\pi^-$ decay in a dipole spectrometer; the event is accepted if the invariant mass is equal to that of the K, and the direction of the decaying K_S is the direction of the incoming beam. The momentum of the decaying K_S is determined; and the position of its decay. We will record the $\pi^+\pi^-$ decay intensity, as a function of distance from the regenerator (z) and kaon momentum. There will be an efficiency $E(z,P_K)$ for this detection, which we will measure by studying the CP violating decay $K_L \to \pi^+\pi^-$ with no target present.

We will transform at once into a dependence, $I(z,P_K)/E(\tau,P_K)$, on kaon proper time and momentum. By use of the equation 1-5 we will determine $|\rho(P_K)|$ and $\phi_f(P_K)$, as discussed in more detail in Appendix D.

Then equations 1-2, 1-3 and 1-6 enable us to determine:

$$\sigma_{total}(K_oP) - \sigma_{total}(\overline{K_o}P) = \frac{4\pi}{k} \text{ Im } [f(0)-\overline{f(0)}]$$

to an accuracy of 10% up to 160 GeV and slightly less accurately to 200 GeV. We also determine:

$$\phi_f = \text{Arg } \{i[f(0) - \overline{f(0)}]\}$$

to 10%.

These two parameters, determined as a function of P_K are the physical information obtained in this experiment. As explained in Section II these are exciting parameters to know, and should be known at as high energy as possible, as soon as possible.

In addition to this fundamental and important measurement, there are many other processes which might be investigated if sufficient manpower is available. Professor Wattenberg has outlined some of the possibilities in his 1968 Summer Study Report C.1-68-18. We will not discuss these possibilities in this proposal.

Given that one can gain a substantial advantage over conventional charged kaon scattering by doing regeneration experiments, one might still ask how to do such experiments to gain the best possible information at the highest energy and at the earliest possible date. Our view is that this question is best satisfied by doing the regeneration in liquid hydrogen from an internal target at the smallest practical beam angle.

We suggest the internal target because it can provide kaon energies a good deal higher than can be practically attained in the presently planned neutral beam in Area II. This is true mainly because one cannot target 400 GeV protons in Area II; as a result, the angles at which one can get an appreciable flux of 200 GeV kaons are completely under the proton diffraction peak and the neutron flux is overwhelming. This was discussed (for example) by Smith in the 1968 NAL Summer Study (B.4-68-17). Because we view a target on which 400 GeV protons are incident, we get a substantial increase in net kaon production above 160 GeV, relative to the production by 200 GeV protons. The diffraction peak is only half as wide in laboratory angle, and our gain in kaon to neutron ratio is exponential. In this difference lies our salvation and our motivation.

Of paramount importance in the target question is the fact that one cannot use the full 10^{13} protons anyhow, so the limitation on radiation and radioactivity in the main ring does not limit the regeneration experiment. This is a very important point ~~if one takes~~ as a primary goal, attaining the highest possible kaon energies. From such a point of view, the internal target approach cannot be improved upon until the advent of Area III in the indefinite future. We believe an internal target is practical and desirable, and we have outlined what appears to be a good approach ~~to~~ getting such a target at the present time in Section III, and in an appendix.

II. Justification of the Experiment

One of the particularly simple predictions of high energy total cross sections is that as the energy tends to infinity, the particle cross sections become equal to the antiparticle cross sections. A stronger prediction is that both tend to a constant.

The latest data on this subject -- including recent data from Serpukhov -- are shown in two accompanying figures.† At 60 Gev/c the π^+p, π^-p; K^+p, K^-p cross sections are not approaching each other as closely as was at one time thought and might even be diverging again at high energies. The data are comparisons of two separate experiments, each with its own, partially separate systematic errors. Thus it becomes hard to measure the difference accurately.

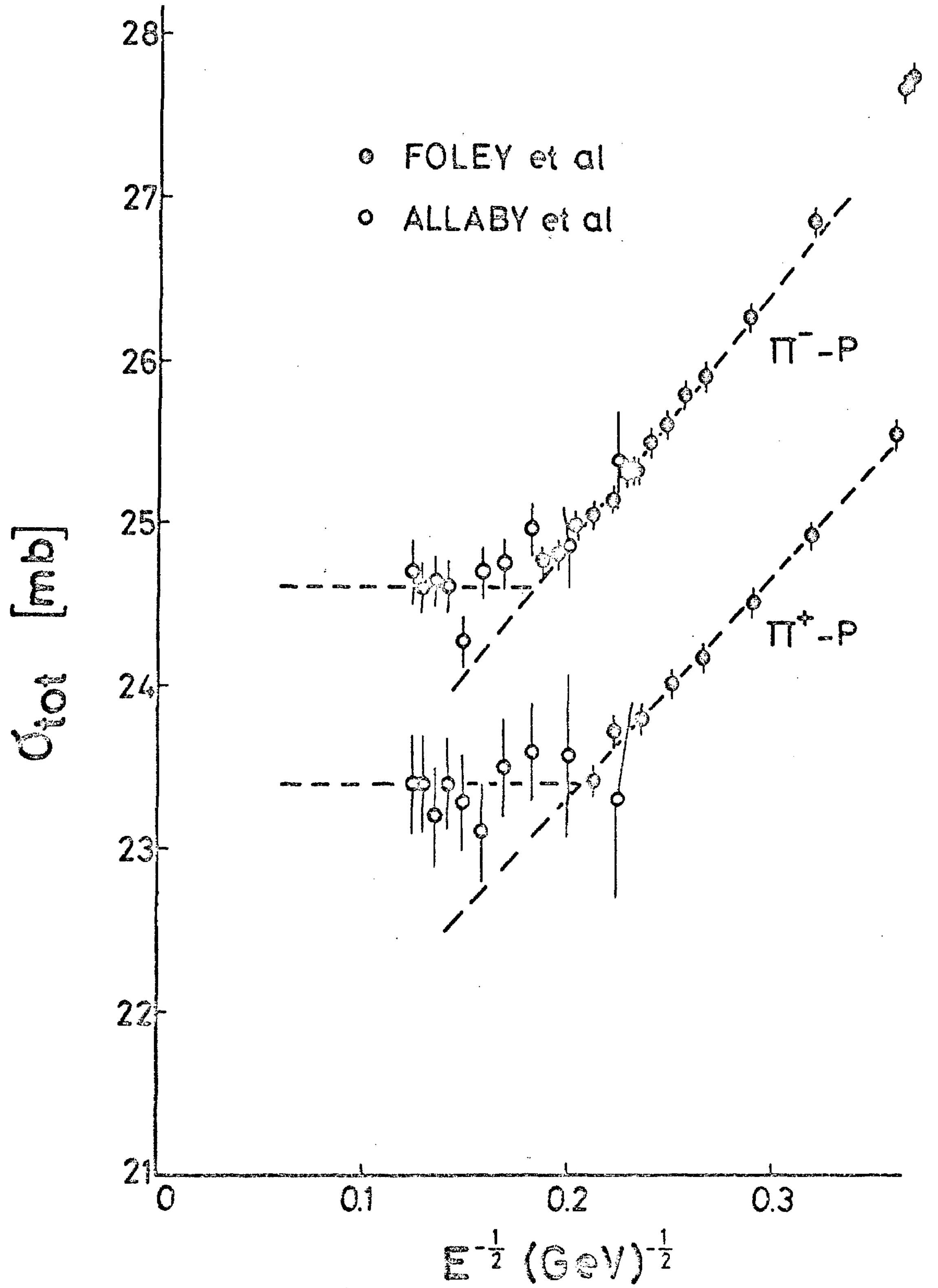
We make various "plausible" extrapolations from the data in order to judge the effects. One is that the K^+p cross section is constant from 20 Gev upwards, and the other, a fit by Barger and Phillips [Phys. Rev. Lett. 24, 291 (1970)] whereby the cross section differences go to zero at high energies.

Experimentally the error on the total cross section measurements from Serpukhov is of the order of 1 mb: this would be inadequate to measure a difference between σ_{K^+p} and σ_{K^-p} if Barger and Phillips fit -- or anything like it -- is correct.

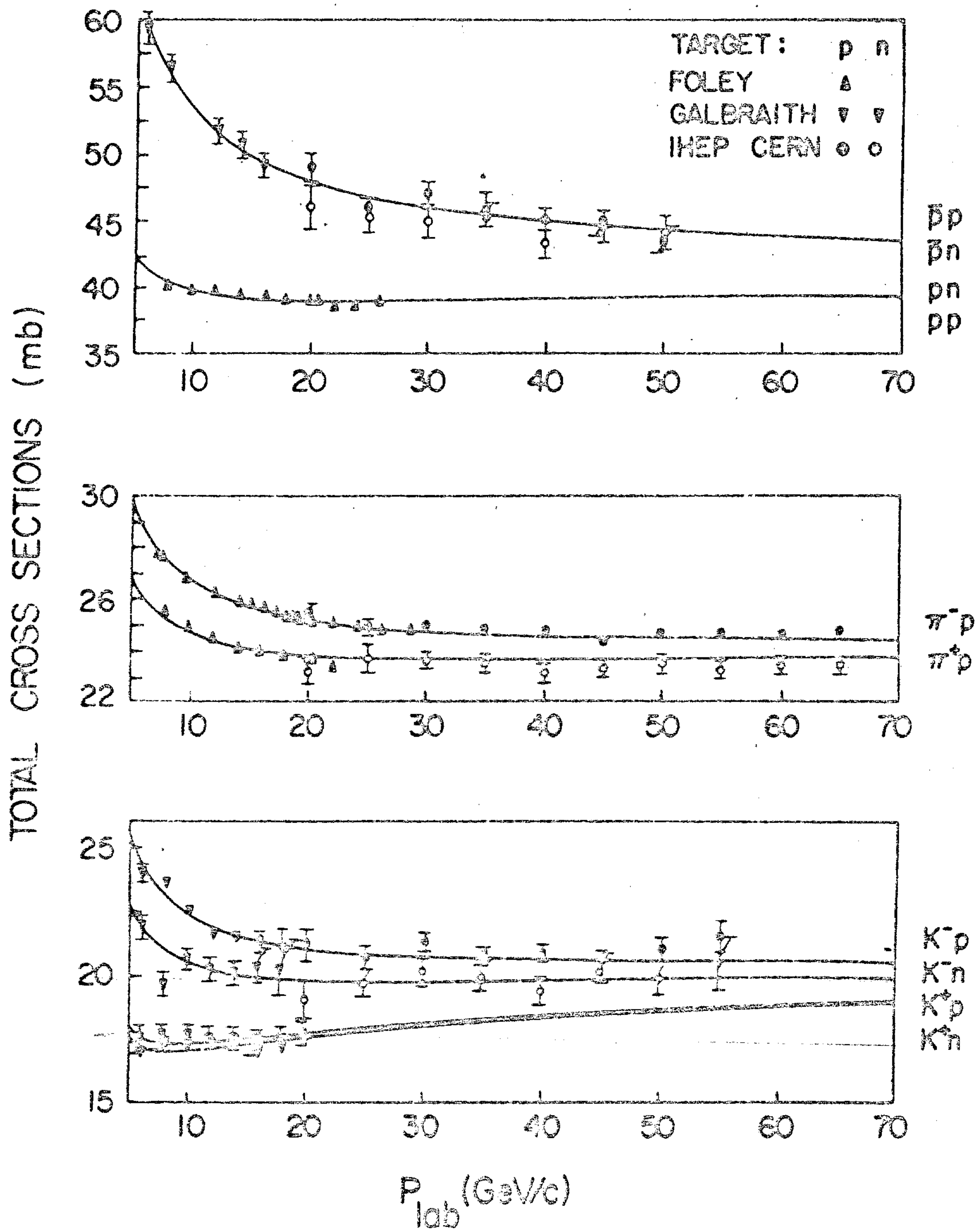
The significance of regeneration measurements in solving these problems is far from original. The importance of these measurements

---

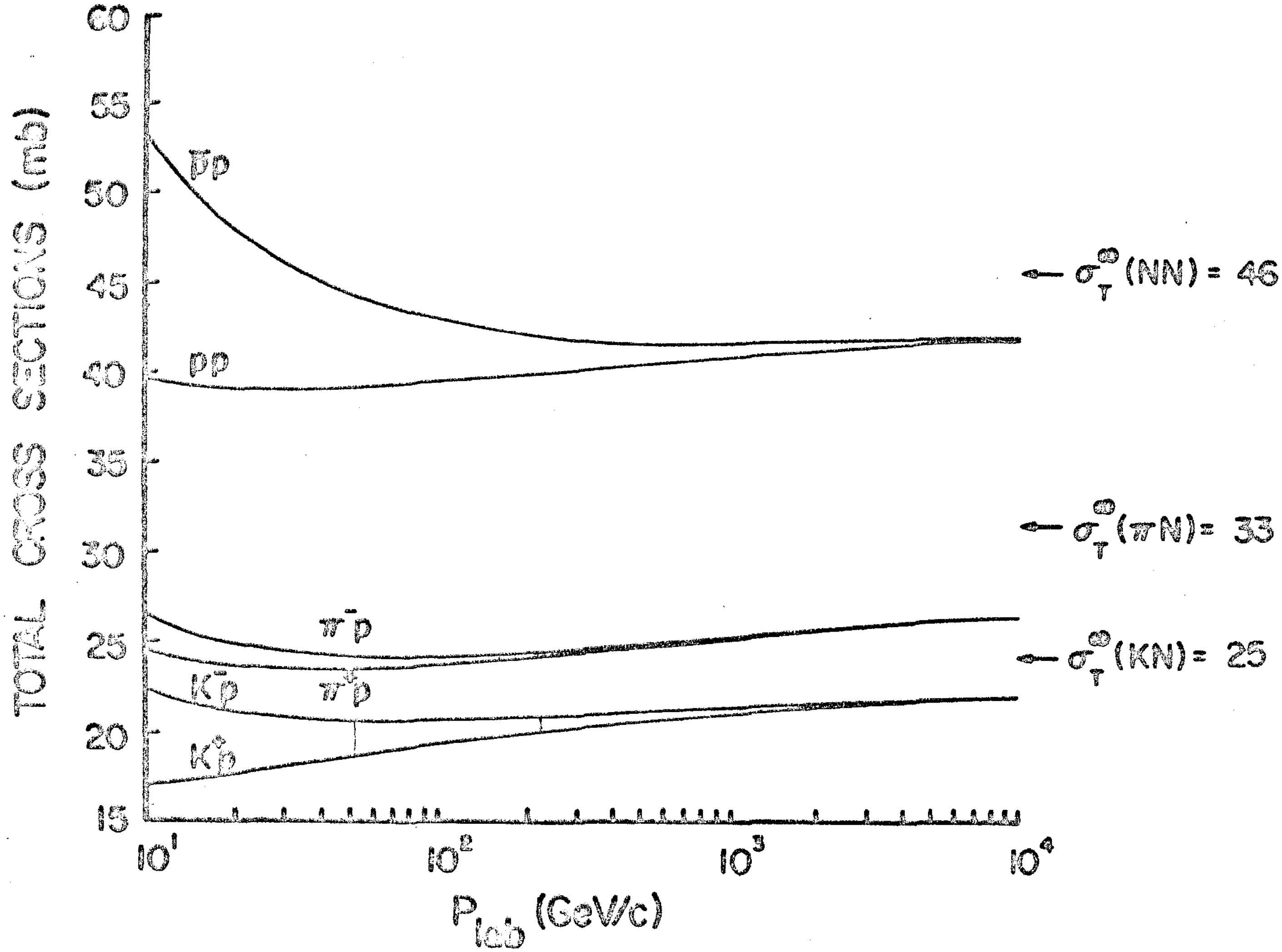
† J.V. Allaby, Proc. Wisconsin Conf., Barger & Durand editors, Madison Wisconsin, 1970.



Total cross sections for $\pi \pm p$ plotted against $E^{-1/2}$, where E is the laboratory energy of the incident pion.



Regge model fit of Barger and Phillips.



Projection of the total cross sections to ultra-high energies, using the Barger-Phillips fit.

for NAL was made clear in the report by Wattenberg to the NAL Summer Study in 1968. We propose to measure the regeneration amplitude in hydrogen which for a thin target is proportional to the difference between K_oP and $\overline{K}_oP$ cross sections; see equations 1-2 and 1-3. In addition we note:

$$\frac{\text{Im } (f-\overline{f})}{k} = \frac{\sigma_{K_oP} - \sigma_{\overline{K}_oP}}{4\pi} \quad \text{(by the optical theorem)}$$

$$= \text{(by isotopic invariance)} \quad \frac{\sigma_{K^+P} - \sigma_{K^-P}}{4\pi}$$

We will also measure the <u>sum</u> ($\sigma_{K_oP} + \sigma_{\overline{K}_oP}$) directly, by absorption.

The real part of the regeneration amplitude is related to the imaginary part by a dispersion relation. Similar dispersion relations may be written for all high energy amplitudes and are linear. The detailed analytic properties determine the subtraction constants and pole terms. We expect, therefore, a relation similar to:

$$\text{Re } [f(E)-\overline{f}(E)] = A + \frac{1}{\pi} \int \frac{\text{Im } [f(E')-\overline{f}(E')]\, dE'}{E - E'}$$

A "bump" in Im $[f(E)-\overline{f}(E)]$ of a Gaussian or Lorenzian shape gives a change in Im $[f(E)-\overline{f}(E)]$ varying as $1/(E-E_o)^2$ whereas the change in Re $[f(E)-\overline{f}(E)]$ varies as $1/(E-E_o)$ and is therefore detectable much further from the bump.

However, we do not measure Re $[f(E)-\overline{f}(E)]$ directly, but only the phase [equation 1-6] $\phi_f = \text{Arg } [i(f-\overline{f})]$.

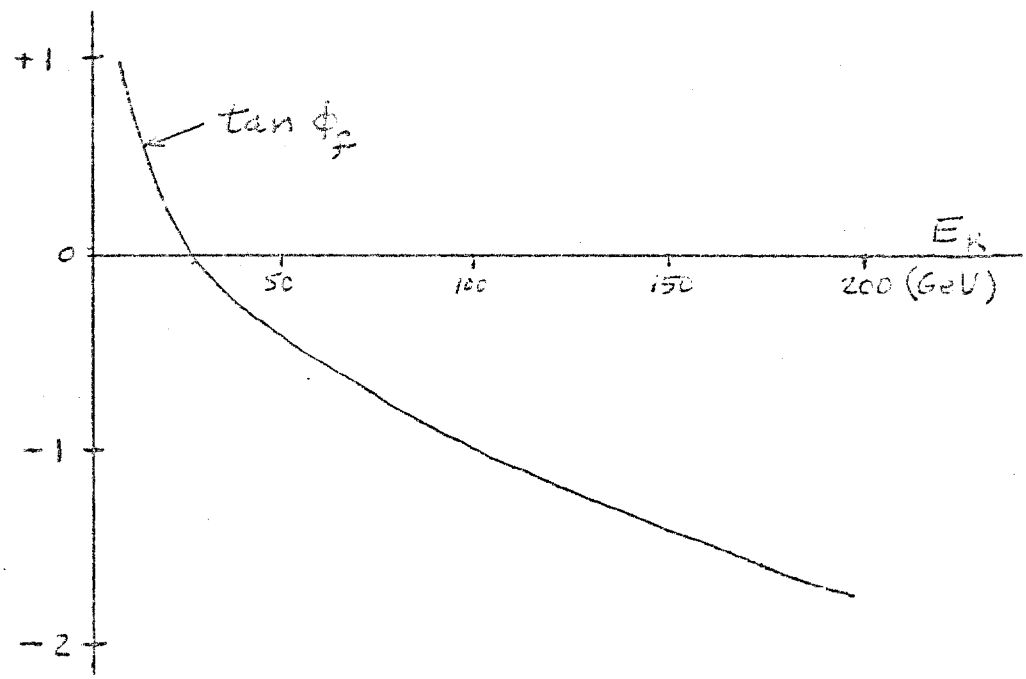
For example, if $\sigma_{K_o P} - \sigma_{\overline{K}_o P}$ is constant, the ratio:

$$\tan \phi_f = - \frac{2}{\pi} \log \frac{E}{M}$$

as shown by Martin.

Since below 6 Bev the phase $\tan \phi_f \approx +1$, we expect a change of sign. A typical curve could be as shown in the figure. But we can also consider the possibility that $\tan \phi_f \to 0$ or stays constant. In any case it must be measured.

Thus the measurement of $\tan \phi_f$ is very important; it is comparable to a comparison (to 1% accuracy!) of the coulomb interference in K^+P and K^-P scattering which are very hard measurements to compare. The only good measurements so far are those of Foley et al [Phys. Rev. Letts. 19, 193 (1967)] on $\pi^{\pm}P$ collisions which are very far from this accuracy.



	20 Gev (Data)	50 Gev If K^+p constant	50 Gev Barger & Phillips	200 Gev constant difference	200 Gev Barger & Phillips
$\sigma_{K^-p} - \sigma_{K^+p}$ millibarns	3	3	1.5	3	0.6
$\sigma_{K^-p} + \sigma_{K^+p}$ millibarns	$\sim$40	$\sim$40	$\sim$40	$\sim$40	$\sim$40
$\dfrac{\sigma_{K^-p} - \sigma_{K^+p}}{\sigma_{K^-p} + \sigma_{K^+p}}$	$7\frac{1}{2}$ %	$7\frac{1}{2}$ %	4%	$7\frac{1}{2}$ %	$1\frac{1}{2}$ %

III. EXPERIMENTAL METHOD

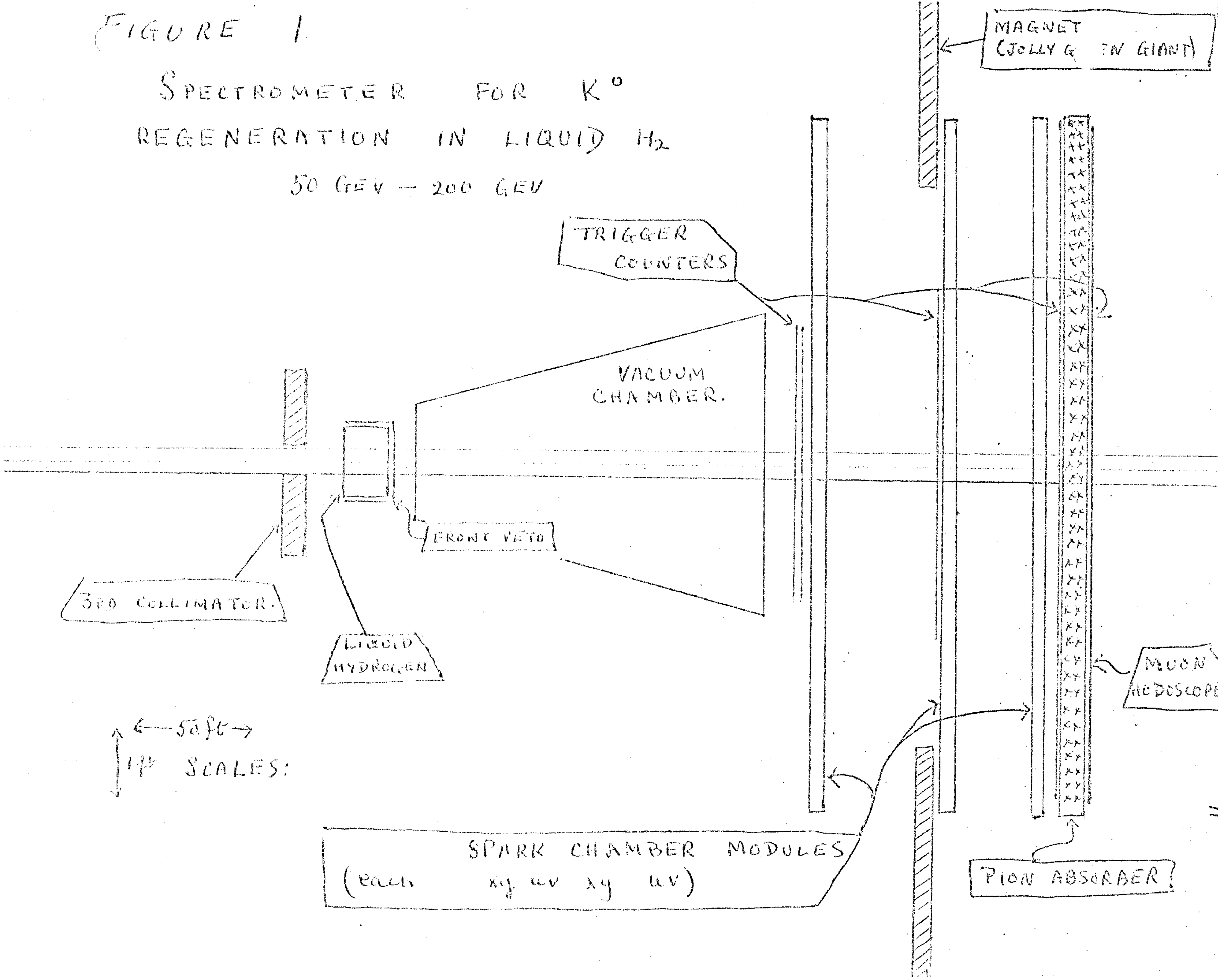
We expect to produce a neutral beam from an internal target at the beginning of one of the long straight sections in the main ring. The beam will emerge into a solid angle of approximately 2.5×10^{-7} ster. at an average angle of 7.5 mr relative to a circulating beam of 400 GeV protons. The number of interacting protons necessary to produce a good experiment is approximately 10^{11} per burst, and perhaps 10^{16} total. The scheme by which we expect to achieve such a beam is outlined in such detail as can be known at present in Appendix A. In general, we believe the requirements can be conservatively met within the design parameters of the system, and more importantly, very early in the life of the accelerator. For the purposes of the remaining discussion, we will assume the existence of such a beam.

The apparatus is shown schematically in Figure 1. The neutral beam will pass through a 2 meter target of liquid hydrogen placed approximately 300 meters downstream from the internal proton target. As the K_L's pass through the hydrogen, regeneration of K_S's occurs and the K_S component is permitted to decay in a 60 meter drift space following the hydrogen

FIGURE 1

SPECTROMETER FOR K^0 REGENERATION IN LIQUID H_2

50 GEV – 200 GEV



target. At the end of the decay region, a wire spark chamber array and analyzing magnet record the trajectories and momenta of the decay particles. Following this magnetic analysis, there is a progression of lead and concrete absorbers interspersed with scintillation counter arrays which are used for triggering and analysis. The entire apparatus is approximately 120 meters long, and requires a building perhaps 6 meters wide and 6 meters high.

Events are recognized by fast electronic logic, and recorded as spark positions in wire chambers of the magnetic core variety. Those chambers are selected over competing methods of data acquisition because they are unexcelled at the present time for reliability, economy, and multitrack efficiency. Additional information pertinent to the identification and analysis of K_S decays is obtained from the scintillation counter arrays. All the data is acquired and processed by a small computer associated with the experiment (now expected to be a PDP-15 being purchased by Harvard). We do not feel it will be necessary to have direct on-line access to a larger computer, but this is always desirable if such a facility is available at this time.

Data will be recorded on magnetic tape in the usual way for processing off-line. We expect that the PDP-15 will be able to reduce somewhat the data on-line as well as monitor the performance of the apparatus.

The geometry of the situation causes the neutral beam to enter the beam area at a depth 5 meters below ground level. This suggests to us that the electronics be placed in a counting room above the apparatus. This is optimal from the signal propagation point of view, and should have cost advantages as well.

The events of interest occur when neutral kaons having energies between 30 GeV and 200 GeV decay into two charged pions in the drift region after the target. This decay mode represents only a fraction of a percent of all the kaon decays which can occur. The contributors to the $\pi^+\pi^-$ mode are the CP violating K_L decays, the coherently regenerated K_S decays, and the incoherently regenerated K_S decays. It is the interference amplitude between the first two processes which gives this experiment its great beauty; the interference enables us to measure not only the <u>magnitude</u>, but also the <u>phase</u> of the difference between $\overline{K}_0p$ and K_0p scattering amplitudes. The phase is a valuable piece of information which may be exceedingly difficult or even impossible to obtain in the analogous experiments being contemplated with charged kaons. It is a primary reason for doing this experiment.

The two charged pions are collected with very high efficiency over most of the decay region in a large H-magnet placed astride the neutral beam. The pions are strongly bent in the magnet and then pass into the absorber at the rear of the apparatus. Their behavior here, combined with information from scintillation counter hodoscopes at the end of the decay region produce a trigger pulse to the spark chambers. After sparking has occurred, the counter and core information is read out to the PDP-15 and preliminary analysis including track reconstruction is made. This partially reduced data is then written on magnetic tape for later analysis. The data is also scrutinized at this point by the monitor program for evidence of malfunction or drift in the apparatus. Other test routines are employed between beam pulses for monitoring purposes. This sort of approach is very standard by now and necessary for doing reliable experiments.

In addition to the two pion decays that we are most interested in, there are K_L decays which can be very valuable for determining the beam momentum spectrum and the acceptance of the apparatus. We will certainly record data of this sort on a shared time basis with two pion decays. In principle, some physics can be gotten here, but is primarily CP violation parameters, and we expect that these will already be well in hand by the time we run. We prefer to view the CP violation at this point as a fantastic interferometer, God given and ready for exploitation in unraveling the energy dependence of the K nucleon asymptotic scattering behavior!

Background in this experiment can be caused by neutron production of K_S in the target and by incoherent K_L regeneration. Most of the background problems are already known in regeneration experiments at low energy; they have been successfully dealt with and no serious energy dependent problems are anticipated.

We have attempted only an outline of the approach we expect to use in order not to obscure the general picture with technical details. These are covered in much more detail in the Appendices for readers who wish to inquire. In general, however, we feel the experiment is technically well within the bounds of current technology, and most of the problems have been met and solved by the authors in previous experiments in this field.

IV. NAL Contributions

This experiment requires the establishment of a neutral beam from a parasite target inside the main ring. A building to house the experiment at the end of the beam transport will also be needed. These two requirements go somewhat beyond the scope of the announced policy of exploiting "nooks and crannies," but we believe the physics which can be accomplished justifies the effort. Preliminary discussions with members of the NAL staff have indicated no serious technical problems with our beam needs.

In addition to the two major items mentioned above, we have a requirement for two more large pieces of equipment of a more conventional nature. The first is a large liquid hydrogen target; the second is a long vacuum chamber. These two items are large in size but ~~as~~ straightforward in design and should not cost a great deal.

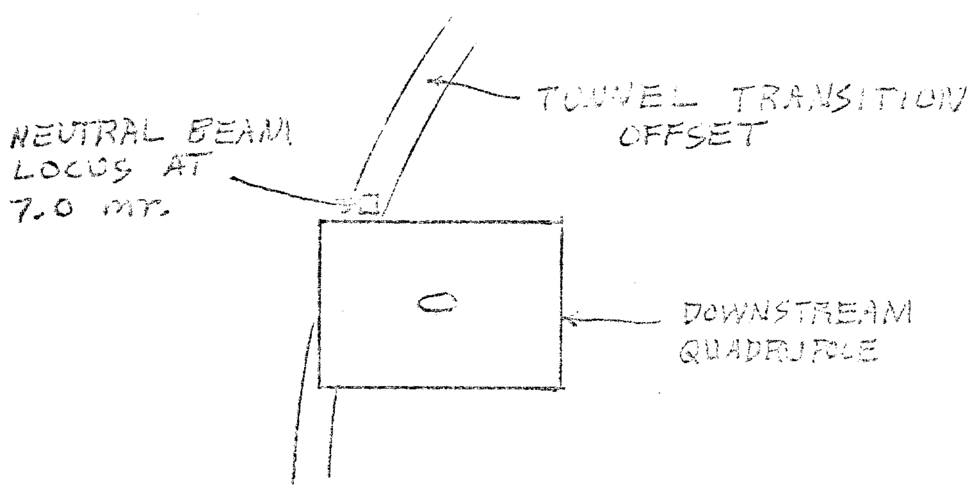
We will also require electric power and cooling water for our analyzing magnet. These requirements are discussed in turn below.

Target and Beam

We envision a target which is designed to intercept 10^{11} interacting protons at a machine energy of 400 GeV. If the machine is initially operated at this intensity or slightly greater, the target will be permitted to intercept a fair fraction or all of the beam. Later, as the machine reaches its peak intensities and accelerates

10^{13} protons to 400 GeV for use in area 3, we would expect the internal target to be changed to intercept a very much smaller fraction of the beam. At any rate, the intensities required for regeneration studies are completely adequate at 10^{11} interacting protons; this number should be compatible with the limits on permitted beam losses inside the main ring as stated in the NAL Design Report.

The beam is extracted in a direction such that it just clears the first magnet downstream of a long straight section. The beam then passes through a brass collimator which determines the solid angle subtended. We envision the collimator as perhaps resting on the first main ring magnet after the straight section or just ahead of it. A sweeping magnet to remove charged particles is placed immediately after the first collimator. A second collimator follows just before the beam exits the main ring tunnel at the point where the transition from a 12 foot diameter tunnel to a 10 foot diameter tunnel occurs. There is an offset at this point which will just permit a two inch diameter pipe to carry the beam out of the tunnel. The locii of the first downstream quadrupole and the tunnel transition as viewed from the target are shown in the diagram below:



This geometry limits the neutral beam to a closest approach of 6.7 mr; we will attempt a beam at an angle more like 7.0 mr for safety's sake.

The beam is then transported a sufficient distance to clear the main ring earth shield. This may be 800 to 1000 feet from the target. At this point the beam enters the experimental area and passes through a final collimator. The first collimator is the stop of the system. The second and third act only to intercept the beam halo. A vacuum transport of the beam is necessary from the target to the exit of the third collimator. The beam transport pipe should be large enough so that earth shifts will not cause it to intercept the beam.

Experimental Area

The requirements of the experimental area are governed by the K_S decay length. This decay length is 5.2 meters for a 100 GeV kaon. About 6 lifetimes are necessary for development of a complete spatial diffraction pattern, and this corresponds to a decay path of about 60 meters at 200 GeV. Above 200 GeV, the kaon flux falls off so rapidly that there are not enough events to pursue the complete pattern, and we need not have a full 6 lifetimes.

In addition to the 60 meters needed for the decay region, we require about 10 meters in front for the third beam collimator and a liquid hydrogen target. Behind the decay region, we place a magnetic spectrometer which is preceded and followed by sets of wire core chamber modules. An absorber-counter array stands behind the magnetic spectrometer. These items will require another 40 meters total. The total length of the apparatus and hence the building becomes 110 meters. The transverse dimensions of the building are set primarily by convenience, but a sensible size might be 6 meters wide and 6 meters high. Access to the rear of the building by truck should be provided in order to install and remove heavy equipment. An overhead crane with ~~maybe 40~~ 50 tons capacity would be extremely useful. The largest part of the target weighs 45 tons. Electronics space, computer space, and working space might be provided in a room above the magnet region. The beam height at the target is about 5 meters below ground, so an excavation will be necessary for the building.

Hydrogen Target

The optimum length of a target for $K_L - K_S$ regeneration depends upon the anticipated asymptotic behavior of the $K_o p - \overline{K_o} p$ cross sections. Since the difference in these cross sections is the object of investigation, it is not possible to know the optimum value *a priori*. What we do in this case is to specify a 5 meter long target with a diameter of about 30 cm. The physics of the neutral kaon system demands that we vary either the length or the density of the regenerator to separate the coherent effect from certain backgrounds and to elicit the phase in an optimum way. We believe at present that the density method is superior, particularly from the viewpoint of freedom from systematic error. A target which will stand 10 atmospheres of hydrogen gas at 32 degrees K temperature can be combined with a regular liquid hydrogen run to give a density variation of a factor 4. This will permit optimum separation.. Such a target is practical.

Vacuum Tank

The decay region for a high energy kaon experiment becomes so long that one is worried by the amount of helium gas which must be traversed by the beam as well as by the decay secondaries. The secondary pions multiple scatter here and some resolution is lost. Of more serious concern is the production of false triggers by neutron interaction in the helium gas. To be on the safe side, we must assume that the decay region is maintained in vacuum.

The decay region is only 30 cm in diameter at the target end, and increases linearly to 150 cm at the magnet end. The vacuum tank might consist of five or more circular cylinders of increasing diameter and joined by sealed matching rings. Thin mylar or stainless steel windows are needed at each end.

Clearly a vacuum tank of this size is a serious safety hazard, and appropriate safety measures will have to be maintained. A set of heavy domed end covers will have to be provided to slam shut on window failure, and interlocked to close before the experimental area can be entered by people. This is an engineering problem of some detail. The thickness of the downstream window is not critical, and a fair safety margin should be built in.

Other Items

Since the proposed kaon area is likely to be rather remote from the main end stations, special notice will have to be taken of the usual requirements for electric power and magnet cooling. The magnet we contemplate using requires up to 800 kw of power. Our electronic equipment and the PDP-15 computer will represent rather standard 115 V loads.

Special Hazards

The large liquid hydrogen targets and the long vacuum chamber are the primary safety hazards. Other secondary hazards are the usual ones of large, strong magnetic fields and photomultiplier tube high voltages. The entire area will also have a fairly high radiation level in the vicinity of the beam while the experiment is running. These safety hazards suggest that the experiment shall be locked and interlocked while running. A beam stopper preceding or behind the first collimator is required for safety when people are in the area. A possible alternative to the stopper might be an interlock with the target flipping mechanism.

V. Logistics and Support

The proposers of this experiment in collaboration with others as stated above expect to provide all the apparatus required for the experiment not explicitly requested of NAL in Section III. This includes the large magnet, its associated wire chambers, all counters and electronics, plus a small on-line computer. We are investigating the possibility of a diesel generator for the magnet if this is thought to be a problem for the laboratory.

Because we would like to see this experiment appear in the very early operating period of the accelerator, we have set up an internal schedule here at Harvard aimed at completing the apparatus by next summer. This schedule of course assumes an equitable sharing of the work load with our collaborators.

Schedules are notoriously hard to maintain in high energy physics. We believe this is in large part due to the fact that a substantial fraction of the work is developmental rather than production. For this reason we have chosen an instrumentation approach which has been rigorously proved in a series of CERN neutral kaon experiments, under the leadership of Professor Carlo Rubbia who will (see personnel) help us with this instrumentation. One of the proposers (Professor Pilcher) has worked intimately with the CERN apparatus and will be responsible for constructing the wire chambers and their associated readout electronics. The scintillation hodoscopes are of course completely standard technology, and can just be specified and built. Our collaborators have indicated an interest in this aspect of the project, particularly with respect to the fast electronics for the trigger.

The software for track reconstruction using the core system has been brought to a high art both by the CERN group and by ourselves at Harvard. We are not sure which system will be used, but we will have a post-doctoral fellow available here for coping with it full-time.

A large fraction of the effort necessary to produce a working apparatus is the test and evaluation program. The magnet which we hope to use is now resting on the floor of the CEA. We expect to map the magnetic field and dress this magnet with core chambers as it stands, and later test it in place with a beam of electrons. In the test phase, the computer will be available with its software for system checks. All this can be done in Cambridge before moving to NAL.

Another important ingredient for a successful experiment is the maintainance of a close liason among the groups involved and with the laboratory. One of us (Professor Kirk) will take this responsibility for the Harvard group.

It is perhaps useful to mention at this point that the apparatus to be used in this experiment is identical with that necessary for the μp inelastic scattering experiment proposed for a later period when the muon beam is available. This degeneracy in apparatus is very important from the practical point of view in that it permits us to concentrate our staff and facilities to a great extent and saves money besides. With the size and cost of experiments rising so rapidly, we expect this to become a standard approach.

Finally, with regard to time schedules, we wish to complement the ebullient spirit of the laboratory by getting our apparatus ready to ship to Batavia by summer of 1971. In this way, if all goes well, an experiment of major importance can be performed with the first 10^{16} protons accelerated to 400 GeV!

Beam Requested

Our experiment needs 500 hours of accelerator operation at 400 GeV with a duty cycle of 0.1, with 10^{11} protons/pulse interacting on the target.

Apparatus Requirements

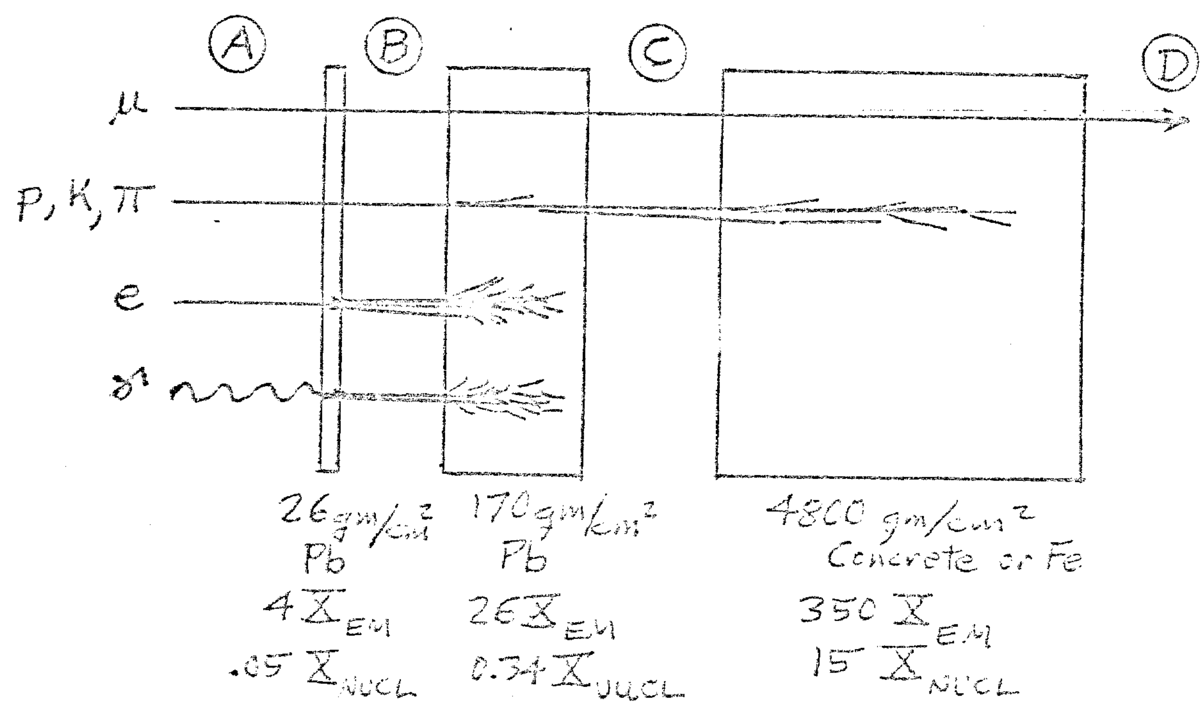
Apparatus	Supplier	Estimated Cost
Magnet (requested from CEA)	CEA	---
Moving magnet	Harvard	$ 30,000
Magnet measuring	Harvard	10,000
Power supply (750 kw regulated, variable only over small range)	NAL?	100,000
Wire spark chambers (~40,000 cores)	Harvard	100,000
Scintillation counters (some existing)	Harvard	10,000
Beam pipe	We hope	30,000
Collimator	NAL can	1,000
Target	provide	10,000
Concrete Pad or building	them	180,000
Computer (PDP15) 1/2 bought	Harvard	40,000
Electronic equipment, 1/2 bought	Harvard	20,000
Lead and steel absorbers for electromagnetic and hadron absorbers in trigger	Harvard or NAL, as convenient	20,000

APPENDIX B

Trigger and Event Signature

The decays of interest constitute only a fraction of a percent of all the kaon decays which occur. As a result, we must develop a trigger which accepts two charged pions with high efficiency and rejects very strongly the vastly more popular CP conserving K_{e3}, $K_{\mu 3}$, and $K_{3\pi}$ decays. We must also veto charged particles emerging from the target with very high efficiency in order to eliminate neutron and kaon induced events. We believe such a trigger can be made if a vacuum decay path is provided, and possibly even if we are forced to use helium bags.

Consider the diagram shown below:



The trigger condition we designed is to observe exactly two "spots" or charged particle tracks at each of the levels A, B, and C and nothing at D. This will record the impact of two 10 GeV or greater pions with an efficiency of 99% or greater. The other K decays are eliminated as follows:

K_{e3}. We observe only one pulse at C and two at A and B. This is because the electron showers and the shower is entirely absorbed between B and C. The trigger rate from K_{e3} is less than 0.1%.

$K_{\mu 3}$. Here we veto on the muon which penetrates the concrete absorber and is recorded at D. The probability of triggering here is about 0.01%, corresponding to the inefficiency of the D Plane counters.

$K_{3\pi}$. The neutral mode is absolutely negligible as it has only photons or electrons in the final state. The charged mode is suppressed by a factor 70 corresponding to neither of the photons from the π^o decay converting in the lead converter between A and B. Additional photon detectors will be placed in front of the magnet to supplement the phase space subtended by the main counter array at point B. The net trigger rate from $K_{3\pi}$ relative to the two pion decay trigger will be about one to one. We can tolerate this.

All other processes must be due to beam interactions in the target. This means we must have a very good anticoincidence counter just downstream of the target and preceding the vacuum tank which constitutes the decay space. We can expect another small trigger rate from accidental coincidence, but we do not expect this to be large. All told, we expect our trigger rate to the spark chambers not to exceed the number of 2π decays by more than a factor of two. The 2π events will be primarily due to coherent K_L-K_S regeneration and non-coherent K_L-K_S regeneration at small momentum transfer. We expect neutron induced K_S's to be vetoed very efficiently by the front veto and our trigger requirement. Additional veto counters may be placed around the target if we feel it necessary at the time.

APPENDIX C

KAON YIELD AND EVENT RATE

The minimum beam angle that is practical with an internal target is 7.0 mr. We assume 10^{11} interacting protons per pulse at 400 GeV with a duty factor of 0.1. These numbers are derived from the NAL Design Report, and are regarded as best estimates rather than fixed values. The neutral kaon fluxes are taken to be equal to the sum of K^+ and K^- production at the same energies and angles. Half the neutral kaon flux survives as a beam of K_L. One half of this flux can be assumed to be lost in the gamma ray attenuator preceding the first collimator.

We estimate the beam intensity by scaling the FAMC fluxes in SS-134 (1969) by Nezrick for production by 200 GeV protons to 400 GeV with the scaling formula:

$$\frac{d^2N(E_p, E_K, \theta)}{dE_K d\Omega} = \left(\frac{E_p}{200}\right) \frac{d^2N(200, E_K', \theta')}{dE_K d\Omega}$$

where:

$$E_K' = \left(\frac{200}{E_p}\right) E_K$$

$$\theta' = \left(\frac{E_p}{200}\right)$$

This scaling formula assumes that the event multiplicity does not increase appreciably from 200 to 400 GeV. Such an assumption should be safe.

With the assumptions above, assuming a solid angle of 2.5×10^{-7} ster, and a detection efficiency of 75%, we obtain the fluxes and events shown in Table 1. Again, we must consider these as estimates rather than fixed numbers. The error quoted for $(\Delta\rho^2/\rho^2)$ is based upon a target of 5 meters of liquid hydrogen and a constant asymptotic cross section difference of 3 mb. The number of hours shown corresponds to the scheme of Appendix D. We hope to provide a more detailed presentation of the experimental precision soon.

TABLE 1 – KAON FLUXES, DECAYS, PRECISI

E_K (GeV)	$\frac{d^2N_{K_L}}{dE_K d\Omega}\Delta E_K \Delta\Omega$ (per 10^{11} p's)	$K_L \to \pi^+\pi^-$ (1,500 hrs)	$K_S \to \pi^+\pi^-$ $\left(\frac{\rho}{\eta_{+-}} = 5\right)$ (167 hrs. - tgt full)	$\sigma\left(\frac{\Delta\rho^2}{\rho^2}\right) =$ (percent)	
20	6.0×10^5	9.5×10^6	3.6×10^6	< 1%	
40	3.0×10^5	3.0×10^6	1.8×10^6	"	
60	1.2×10^5	9.3×10^5	7.2×10^5	"	
80	3.7×10^4	2.1×10^5	2.2×10^5	"	
100	1.5×10^4	7.0×10^4	9.0×10^4	1.1%	
120	6000	1.2×10^4	3.6×10^4	1.8%	
140	2000	7000	1.2×10^4	3.2%	
160	600	1900	3600	5.8%	
180	160	450	960	11%	
200	50	120	300	15%	
220	12	30	72		
ΣN_K	$\sim 1.0 \times 10^6$				
ΣN_n	$\sim 2\text{-}5 \times 10^7$				

Kaon Flux = SS-134(1969), F. Nezrick

neutron Flux = B.5-68-24, T. G. Walker, 1968 UdZ

APPENDIX D

RUNNING CONDITIONS

Target full/Target empty determination of the regeneration $K \to 2\pi$ rate from the liquid hydrogen:

Let us assume we determine the $K \to \pi^+\pi^-$ decay rate over the given (60m) decay volume in the following conditions:

1) hydrogen target full (density, d = 1)

2) hydrogen target empty (d = 0)

3) hydrogen target at reduced density (d $\sim$ 1/5)

The measurement 3 is necessary since the standard target full-empty technique does not take into account the coherent interference effects between the hydrogen of the target in one case, and the CP violating amplitude $K_L \longrightarrow \pi^+\pi^-$ or the residual regeneration from material in the empty target in the other.

Let us define a given point (x,y,z) of the decay volume:

ρ_H = (complex) regeneration amplitude

from the liquid hydrogen (d = 1); for d $\neq$ 1, the corresponding amplitudes scales like $d \cdot \rho_H$.

$$\eta_{+-} = \left(K_L \to \pi^+\pi^-\right) / \left(K_S \to \pi^+\pi^-\right) \text{ amplitude ratio}$$

a = residual regeneration amplitude due to the windows, etc. for an empty target.

Then the number of observed events from an infinitesimal volume around the point (x,y,z) is given by:

$$I\ (d;\ x,y,z) \sim d^2\ |\rho_H|^2 + |n_{+-} + a|^2 + 2d|\rho_H|\ |n_{+-} + a|\ \cos\phi$$

where:

$\phi = \text{Arg}\ [(n_{+-} + a)\cdot\rho_H]$

$d = 1$ is for the full target

$d = 0$ for an empty target

$d \ll 1$ for the low density run.

Then:

$$\frac{I\ (d;\ x,y,z) - I\ (0;\ x,y,z)}{d^2} \sim (\rho_H)^2\ [1 + 2\ \frac{1}{d} \left|\frac{n_{+-} + a}{\rho_H}\right| \cos\phi] \qquad [1]$$

Therefore the correction for interference effects can be done by performing the target full-target empty subtraction at $d \to \infty$ or more simply by extrapolating expression[1] to the limit $\frac{1}{d} \to 0$.

Integrating the decay rate over any arbitrary decay volume with a detection efficiency $E(x,y,z)$ one gets:

$$I\ (d) = \int_V I(d;\ x,y,z)\ E(x,y,z)\ dV$$

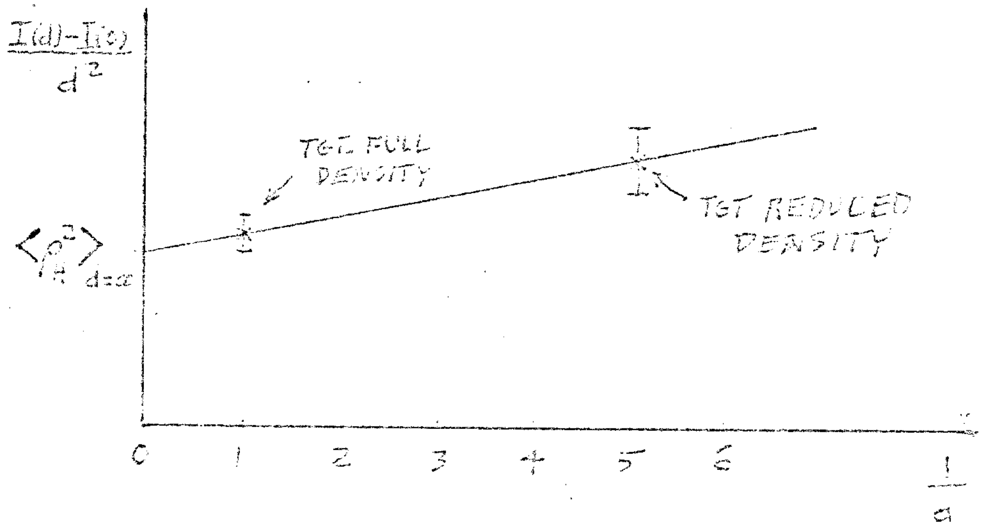
and expression[1] becomes:

$$\frac{I(d) - I(0)}{d^2} \sim \langle |\rho_H^2| \rangle\ [1 + \frac{1}{d}\ A]$$

where:

$$A = \int_V \left| \frac{n_+ + a}{\rho_H} \right| E(x,y,z) \cos\phi \, dV$$

is taken as a <u>phenomenological</u> parameter to be determined empirically from the 1/d dependence and $\langle |\rho_H^2| \rangle$ is the average regeneration amplitude from hydrogen alone.



We note that this plot can be make at each position z where the intensity is measured. The extrapolated value $|\rho_H|^2$ should be independent of z, and of efficiency. The statistical error on $|\rho_H|^2$ will clearly be worse for large z where the regeneration amplitude becomes neglible compared with the CP violation amplitude: we will weight the values of $|\rho_H|^2$ obtained by the statistical weight of $|\rho_H|^2$ and <u>not</u> by the number of counts.

APPENDIX E

SCHEDULE FOR EXPERIMENT PREPARATION

Because of the early suggested time of the experiment, it is important to show that we can prepare the experiment quickly.

At Harvard we have built good, large wire chambers with magnetostrictive read out. Some exist and could even be used for this experiment.

However we believe that an NAL experiment deserves the superior multispark efficiency available with the core read out chambers. However we have experimental numbers on the time to make these chambers; we will copy the CERN design. The general priority has been discussed and approved by the Harvard University High Energy Physics Committee.

Spark Chamber Schedule

September 1970:	Modify CERN drawings for our geometry and winding machines
October 1970:	Bid on spark chamber frames
November, December 1970	Contruction of spark chamber frames
January-April 1971	Winding of spark chambers (4 per month)
February-May 1971	Test of chambers

Computer Delivery Schedule

April 1970	PDP 15 ordered (less magnetic tape)
October 1970	PDP 15 arrive; program writing and test of read out begins
October 1970	Order magnetic tape drive
April 1971	Tape drive arrives
May 1971	Final test of program

Electronic Read Out

September 1970	Modify CERN drawings for core read out
October 1970	Order cores (assembled in frame) and read out modules
February 1971	First cores and modules arrive. Test with PDP 15 and chambers
May 1971	Final test
June, July 1971	Final test of system

Scintillation Counters: Absorbers, etc.

Fall 1970	Final decision on trigger logic
January 1971	Draw up and order
April 1971	All scintillation counters available
July 1971	Absorbers delivered directly to NAL